# Intermediate-Band Photometry of Stars in Three Clusters Containing Classical Cepheids

Edward G. Schmidt
*University of Nebraska at Lincoln*, eschmidt1@unl.edu

# INTERMEDIATE-BAND PHOTOMETRY OF STARS IN THREE CLUSTERS CONTAINING CLASSICAL CEPHEIDS

EDWARD G. SCHMIDT[a)]
Behlen Observatory, University of Nebraska at Lincoln, Lincoln, Nebraska 68588
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## ABSTRACT

Four-color and Hβ photometry has been carried out of stars in three sparse and distant clusters which are thought to contain Cepheids. From these data the distance moduli and color excesses of the clusters have been derived. In general the new values agree with those in the literature but are somewhat more precise.

### I. INTRODUCTION

This paper is the sixth in a series giving intermediate-band photometry for B stars in clusters containing classical Cehpheids. The motivation for this project and the methods used were discussed in the first paper (Schmidt 1980). The present paper concerns three very sparse clusters, the anonymous cluster near CV Mon, Ruprecht 79, and Lyngå 6. Although these clusters contain very few stars and it has been difficult to determine precise distances or even in some cases to establish firmly their existence, they were observed in order to help alleviate the scarcity of calibrating Cepheids.

The anonymous cluster near CV Mon (period = 5.4 days) was first pointed out by van den Bergh (1957) and subsequently studied by Arp (1960) using *UBV* photometry. Arp concluded that the cluster was real and derived the luminosity of CV Mon. However, Preston (1964) obtained spectra of 27 of the brightest stars and found that most were not reddened B stars as Arp had assumed but rather were foreground F and G stars. This led him to question the distance modulus derived by Arp and even the existence of the cluster. However, as pointed out by Turner (1978) the existence of even the nine B stars which Preston found in the vicinity of CV Mon suggets that the cluster is real. On the basis of star counts and further photometry, Turner argued that the cluster exists and that CV Mon is a member.

It was suggested by Tsarevskij, Ureche, and Efremov (1966) that the cluster Ru 79 contains the Cepheid CS Vel (period = 5.9 days). Moffat and Vogt (1975a) and Harris and van den Bergh (1976) obtained *UBV* photometry of stars in this cluster and derived distance moduli and color excesses. However, the precision of the results is compromised by the paucity of the cluster and the serious contamination by field stars. The resulting true distances moduli in the two papers differed by three-quarters of a magnitude. Therefore, this cluster clearly requires further investigation in order to render it useful for calibration purposes.

Tsarevskij *et al.* also suggested that the cluster Ly 6 (Lynga 1964) contained the Cepheid TW Nor ($P = 10.8$ days). Photometric observations on the *UBV* system of stars in this cluster have been made by Madore (1975), Moffat and Vogt (1975b), and van den Bergh and Harris (1976), while The (1977) observed it on the Walraven five-color system. The difficulties presented by this cluster are illustrated by the fact that Moffat and Vogt expressed doubt about its existence. However, the papers of van den Bergh and Harris, The, and Lyngå (1977) seem to confirm the reality of the cluster. Here, too, there is a range of derived distance moduli with Madore finding an apparent modulus of 16.2 and Lyngå and van den Bergh and Harris finding 15.2. Thus, further observations are needed.

### II. THE OBSERVATIONS

It is important to have as large a sample of stars as possible in each cluster. However, since these stars are faint for this type of photometry and require considerable telescope time to observe, it is necessary to be selective in choosing stars which are likely to prove to be members. Preston's (1964) spectral types are used to select stars in the CV Mon cluster. Except for three of the brightest stars, only those designated as B by Preston were included; seven of the nine stars of that type were observed. For Ru 79 there are not spectral types available and the selection was based on the *UBV* photometry. All the stars brighter than $V = 14$ which were not too crowded for photometry and which lay near the apparent main sequence of the cluster were observed. In Ly 6 there are five stars which were regarded as tentative members by both Moffat and Vogt (1975b) and The (1977). All five were included in the present photometry. There were between five and ten stars observed for each of the clusters. We must expect that the number of members will be even less. Given the sparsity of the clusters and the faintness of the stars, it is not possible to improve greatly on this situation and we will have to try to get as much information as possible out of this sample.

[a)] Visiting Astronomer, Cerro Tololo Inter-American Observatory and Kitt Peak National Observatory, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract from the National Science Foundation.

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Table I lists the stars which were observed. The first column gives the name of the cluster and the second identifies the star. The designations of the stars in the CV Mon cluster come from Arp (1960) and Preston (1964), while those in Ru 79 are from van den Bergh and Harris (1976). For Ly, 6, Lyngå's (1977) star numbers are listed. The $V$ magnitudes listed in the third column were taken from papers by Arp (1960) and Turner (1978) for the CV Mon cluster, from Harris and van den Bergh (1976) for Ru 79, and from van den Bergh and Harris (1976) for Ly 6.

The present photometric observations were carried out at Kitt Peak National Observatory using the 1.3- and 2.1-m telescopes and at Cerro Tololo Inter-American Observatory using the 0.9- and 1.5-m telescopes during 1979 and 1980. Standard four-color filters were supplied by the observatories while the same H$\beta$ filters were used for all the observations. These H$\beta$ filters were selected to be well matched in wavelength to avoid color terms in the transformations. Observations were made of equatorial secondary standards to refer the data to the standard system. Among these secondary standards are B stars with reddenings as high as $E(b-y)=0.99$. A preliminary discussion of the reddened standards is given in a previous paper (Schmidt 1982) and a full discussion of all the secondary standards will be published later.

Columns 4–9, 11, and 12 of Table I give the mean photometric indices and their standard errors. Since these stars are faint and a variety of telescopes were used under various sky conditions, the errors vary considerably. Therefore, the internal standard error for each index has been derived from the individual values and is tabulated (in thousandths of a magnitude) following the index. The number of nights on which four-color photometry was obtained is listed in column 10 of the table, while column 13 gives the number of nights on which H$\beta$ photometry was obtained. Due to the faintness of these stars, especially in the $u$ filter band, the precision is not as good as in my previous cluster studies. However, it is good enough to give useful information and to improve our knowledge of these clusters.

Figures 1 and 2 show plots of some of the photometric parameters. Also shown are the zero-age relations shifted to the appropriate distance and reddening of these clusters. Points representing stars judged below to be nonmembers are circled. Although these diagrams were not used in the discussion of membership, it can be seen that the stars retained as members form tight groups. In both of these diagrams evolution causes stars to move up from the zero-age relation. In Ly 6 all the stars we have observed are evolved, while in the other two clusters a few unevolved stars were found. Ru 79 and Ly 6 appear to be about the same age, while the CV Mon cluster is somewhat older.

## III. THE DISTANCE MODULI AND COLOR EXCESSES

In order to apply the four-color and H$\beta$ calibrations to the photometric data it is necessary to determine the spectral range in which each star falls. As in previous papers of this series, the diagram of $[m_1]$ vs $[c_1]$ was used to separate the stars into those which are early enough to use the B star calibration (Crawford 1978), those which

TABLE I. Photometric data.

| Cluster | Star | $V$ | $b-y$ | s.e. | $m_1$ | s.e. | $c_1$ | s.e. | $n$ | $\beta$ | s.e. | $n$ | Sp. | $V_0-M_V$ | s.e. | $E(b-y)$ | s.e. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CV Mon | D | 12.99 | 0.391 | 2 | 0.112 | 1 | 0.900 | 3 | 2 | 2.777 | 17 | 4 | A | 10.23 | 23 | 0.234 | 13 |
| | G | 13.33 | 0.614 | 9 | 0.276 | 6 | 0.428 | 52 | 2 | 2.565 | 13 | 4 | F[a] | 9.48 | 68 | 0.123 | 20 |
| | J | 13.51 | 0.382 | 16 | 0.110 | 16 | 0.443 | 48 | 2 | 2.628 | 8 | 4 | F | 9.91 | 53 | 0.065 | 16 |
| | M | 13.72 | 0.522 | 4 | 0.000 | 21 | 0.768 | 28 | 4 | 2.801 | 20 | 4 | B | 10.40 | 52 | 0.566 | 4 |
| | N | 13.76 | | | | | | | | 2.798 | — | 1 | | | | | |
| | O | 13.81 | 0.450 | 16 | 0.009 | 26 | 0.865 | 3 | 3 | 2.816 | 20 | 5 | B | 10.89 | 51 | 0.490 | 16 |
| | P1 | 13.73 | 0.513 | 13 | −0.002 | 14 | 0.837 | 15 | 4 | 2.789 | 7 | 3 | B | 10.88 | 27 | 0.550 | 13 |
| | P2 | 13.95 | 0.498 | 17 | −0.047 | 24 | 0.888 | 35 | 2 | 2.743 | 10 | 2 | B | 12.32 | 36 | 0.538 | 17 |
| | P4 | 14.31 | 0.530 | 30 | 0.030 | 2 | 0.916 | 12 | 2 | 2.849 | 34 | 4 | B | 10.62 | 83 | 0.569 | 30 |
| | U | 14.72 | 0.577 | 23 | 0.019 | 20 | 0.938 | 3 | 2 | 2.767 | — | 1 | B | 12.36 | 77 | 0.615 | 23 |
| Ru 79 | I | 11.96 | 0.583 | 8 | −0.037 | 11 | 1.217 | 15 | 5 | 2.769 | 5 | 4 | A0[b] | 10.78 | 13 | 0.555 | 14 |
| | K | 12.30 | 0.487 | 6 | −0.058 | 15 | 0.799 | 8 | 3 | 2.698 | 9 | 4 | B | 11.65 | 18 | 0.529 | 6 |
| | N | 12.85 | 0.400 | 4 | 0.107 | 14 | 0.715 | 19 | 3 | 2.660 | 13 | 4 | F | 11.39 | 36 | 0.124 | 13 |
| | O | 13.00 | 0.323 | 12 | −0.006 | 21 | 0.527 | 25 | 3 | 2.729 | 14 | 4 | B | 11.47 | 29 | 0.388 | 13 |
| | P | 13.10 | 0.414 | 2 | 0.225 | 3 | 0.420 | 13 | 3 | 2.634 | 11 | 4 | F | 9.27 | 27 | 0.056 | 13 |
| | Q | 13.11 | 0.495 | 11 | −0.073 | 10 | 0.697 | 13 | 3 | 2.708 | 6 | 4 | B | 11.82 | 13 | 0.544 | 11 |
| | V | 13.58 | 0.372 | 3 | 0.187 | 8 | 0.418 | 17 | 3 | 2.616 | 14 | 4 | F | 10.13 | 32 | 0.014 | 17 |
| | W | 13.63 | 0.517 | 11 | −0.075 | 16 | 0.672 | 15 | 3 | 2.689 | 19 | 3 | B | 12.75 | 38 | 0.569 | 11 |
| | Y | 13.67 | 0.519 | 23 | −0.110 | 17 | 0.506 | 1 | 2 | 2.717 | 7 | 4 | B | 11.46 | 14 | 0.591 | 9 |
| Ly 6 | 5[c] | 12.46 | 0.942 | 10 | −0.186 | 10 | 0.721 | 18 | 4 | 2.692 | 15 | 3 | B | 9.56 | 54 | 0.999 | 10 |
| | 6 | 13.48 | 0.892 | 14 | −0.156 | 25 | 0.601 | 14 | 3 | 2.693 | 10 | 4 | B | 10.45 | 43 | 0.961 | 14 |
| | 7 | 13.14 | 0.854 | 10 | −0.178 | 24 | 0.181 | 26 | 3 | 2.626 | 12 | 4 | B | 11.90 | 37 | 0.971 | 10 |
| | 8 | 13.47 | 0.891 | 4 | −0.165 | 15 | 0.631 | 4 | 2 | 2.697 | 18 | 3 | B | 10.40 | 36 | 0.957 | 4 |
| | 10 | 13.31 | 0.902 | 17 | −0.179 | 20 | 0.622 | 14 | 3 | 2.672 | 12 | 3 | B | 11.03 | 37 | 0.969 | 17 |

[a] Slightly too late in spectral type for F star calibration. The distance modulus and color excess are based on extrapolation of calibration.
[b] The position of this star in the $[m_1]$-$[c_1]$ diagram indicates that it should be treated as an A0 star. If we consider it a B star we find a distance modulus of 10.43 and a color excess of 0.593 but this requires an extrapolation of the calibrations.
[c] Double star. Both components included in diaphragm.

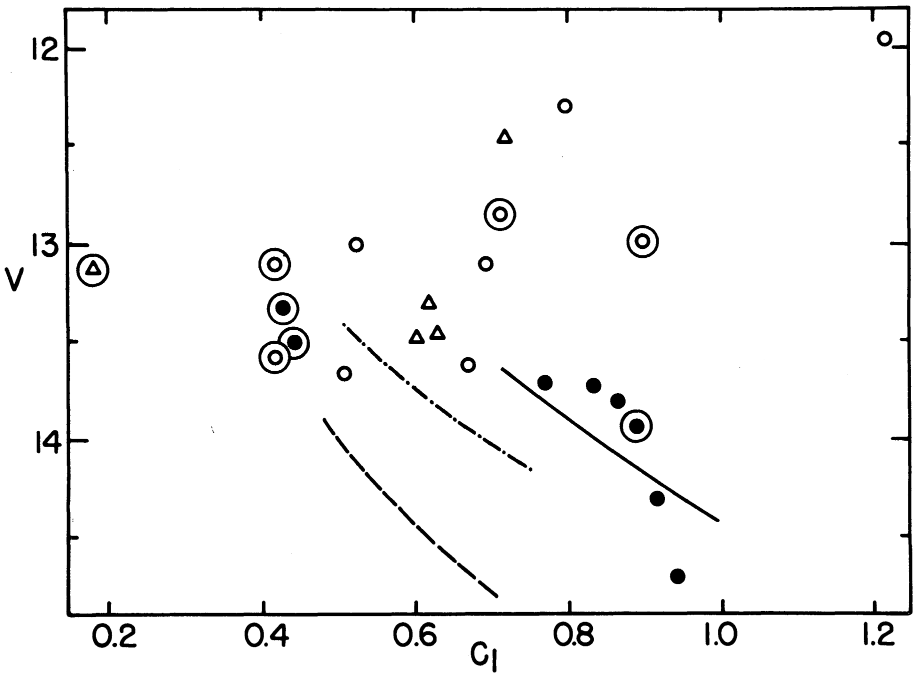


FIG. 1. The diagram of apparent magnitude vs the $C_1$ index for the three clusters. The closed circles represent stars from the CV Mon cluster, open circles those from Ru 79, and the triangles those from Ly 6. Circled symbols denote stars judged to be nonmembers in Sec. III. Also shown is the zero-age relation for B stars shifted to the distance modulus and reddening of each cluster and encoded as follows: solid line, CV Mon; dot-dashed line, Ru 79; dashed line, Ly 6.

are near the temperature of maximum strength of the hydrogen lines [A0 (for which the calibration of Claria 1974, quoted by Eggen 1980) was used], and later-type stars. For the later-type stars the $\beta$ index serves to separate those for which the A star calibration should be used (Crawford 1979) and those for which the F star calibration is appropriate (Crawford 1975). In the case of the CV Mon cluster the spectral types of Preston (1964) provide further guidance; the spectral ranges inferred from the photometry are consistent with Preston's spectral types in every case. The calibration used for each star is indicated in the 14th column of Table I. The distance moduli and color excesses obtained from the appropriate calibration are listed in the 15th and 17th columns. The standard errors are given in units of the least significant digit (hundredths of a magnitude for the distance modulus and thousandths of a magnitude for the color excesses). These were obtained by carrying the photometric errors through the calibrations and represent only the internal errors.

In analyzing the photometry we have used excess ratios of $E(m_1) = -0.32E(b-y)$ and $E(c_1) = 0.20E(b-y)$ and the ratio of total to selective absorption of $A_V/E(b-y) = 4.28$.

A serious problem in determining the distance modulus of a cluster is the selection of stars which can be used for this purpose. In applying the main-sequence fitting method, it is necessary to ignore stars which deviate from the cluster stars in the color-color plots or in the HR diagram and stars which are affected by evolution. Using the intermediate-band photometry it is also necessary to avoid using nonmembers but evolutionary effects are included in the calibration and should in principle pose no serious difficulty. On the other hand, we need to avoid using stars which are outside of the limits of the calibration or which show peculiarities such as emission lines. Bearing these points in mind we must consider the sample of stars for each cluster and determine which stars to use and what errors we might expect to introduce by our choice.

In the CV Mon cluster our choice of stars was guided by Preston's (1964) spectral types as well as the *UBV* photometry. We might therefore expect relatively little contamination in our sample from field stars. Indeed, the three stars which are obvious foreground stars according to their color excesses, stars D, G, and J, all have the spectral types of A, F, or G according to Preston. The remaining stars are all listed by Preston as B stars and all might therefore be expected to be members of the cluster. Omitting the three late stars, the mean distance modulus (weighted according to the standard errors of the individual stars) is 11.2. However, the scatter of the individual stars is nearly twice what would be expected from the errors listed in Table I. Therefore, it is very possible that some of the B stars should be omitted. Omitting star P2 on the grounds that its modulus is three standard errors from the cluster mean yields a mean distance modulus of $10.9 \pm 0.2$ (standard error of the mean) and the two estimates of the standard error of the mean (from the individual star errors and from the scatter of the individual stars) agree well. Therefore, this appears to be the best estimate but given the effects of selection on the mean, the uncertainty is probably somewhat greater than the formal errors suggest. My adopt-

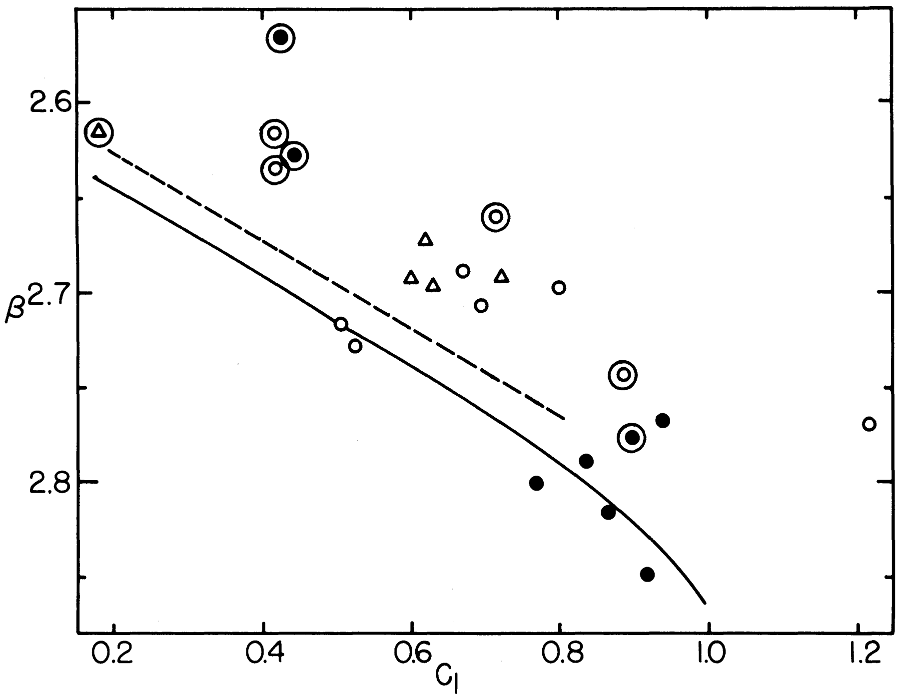


FIG. 2. The $\beta$-$C_1$ diagram for the three clusters. The symbols for the stars are the same as for Fig. 1. The solid line is the zero-age relation for the CV Mon and Ru 79 clusters while the dashed line is for Ly 6.

ed values are listed in Table II. Also listed is the mean color excesses for the same stars and the number of stars used in the means. The six stars which have high enough reddening to be possible members of the cluster are too few to map out any variation in the obscuration. However, the scatter in the color excesses is larger than the individual star errors would suggest and probably indicates some patchiness in the reddening. The reddening for the Cepheid, CV Mon, was taken to be that of star M, which is only about 15″ from the Cepheid.

In Ru 79 there are also three stars with low reddening, stars N, P, and V, which are likely to be field stars. Star 0 has lower reddening than any of the other B stars but is at the correct distance to be a member. Since it is away from the other B stars in the cluster, this might be due to variations in the extinction and this star should probably be retained as a member. Furthermore, stars I and W scatter by a rather large amount from the cluster mean considering their quoted errors. If only the four stars K, O, Q, and Y are considered to be members, the mean distance modulus becomes $11.6 \pm 0.1$, while including I and W as well results in a modulus of $11.4 \pm 0.2$. In the second case, the standard error from the scatter exceeds that expected from the individual star errors by a factor of 3. For this cluster I adopt this value but have increased the uncertainty to reflect the difficulties in selecting stars for the average. The color excesses of the individual stars clearly show evidence of variable extinction and the reddening of star K which is nearest to CS Vel (slightly less than 30″ away) has been adopted for the Cepheid.

All five of the stars we have observed in Ly 6 were considered to be members by Madore (1975), The (1977), and Lyngå (1977), so it is not surprising that the color excesses and distance moduli we derive here are all similar. However, the weighted mean of the distance moduli from Table I is $10.8 \pm 0.4$ (standard error from the scatter), whereas the individual standard errors indicate that the standard error of the mean should be about 0.2 mag. One factor which might contribute to this is that star 5 is double. The components were examined visually and by comparison with stars 6 and 9 the magnitude of the fainter, 5B, was estimated to be about 13.7. Using this value we find the brighter component should have a $V$ magnitude of about 12.9 and correcting for contamination by the fainter star it should have $\beta = 2.682$. Using these values I obtain a distance modulus of 10.36 for star 5. This value is not very sensitive to the assumed magnitude of star 5B so long as it contributes substantially to the total light. For example, if we assumed that the two

TABLE II. Adopted cluster parameters.

| Cluster | $\langle V_0 - M_V \rangle$ | s.e. | $\langle E(b-y) \rangle$ | s.e. | $n$ | $E(b-y)$ Cepheid |
|---|---|---|---|---|---|---|
| CV Mon | 10.9 | 0.3 | 0.562 | 0.010 | 5 | 0.566 |
| Ru 79 | 11.4 | 0.3 | 0.536 | 0.023 | 6 | 0.529 |
| Ly 6 | 10.6 | 0.3 | 0.963 | 0.008 | 4 | 0.980 |

components were equal in magnitude the distance modulus would be 10.31. Using one of these values for star 5 results in a mean distance modulus of $10.9 \pm 0.3$ for the cluster. If in addition star 7 is omitted because it lies almost three standard deviations from the mean, I obtain $10.6 \pm 0.2$. Based on this discussion it is not possible to claim that the distance is any better determined than several tenths of a magnitude. The scatter in the individual color excesses is relatively small and we adopt the weighted mean of the three nearest stars for the Cepheid.

## IV. DISCUSSION

Turner (1978) discussed the *UBV* data for the CV Mon cluster and derived a true distance modulus of $11.21 \pm 0.27$ (probable error) and a color excess of $E(B-V) = 0.77$, which corresponds to $E(b-y) = 0.57$. Both of these values are in good agreement with the present determination. For Ru 79, Harris and van den Bergh (1976) obtained a distance modulus of $12.25 \pm 0.5$, while Moffat and Vogt (1975a) obtained 11.5. The former does not agree well with current value but the latter does. These authors obtained color excesses which correspond to $E(b-y) = 0.56$ and $E(b-y) = 0.61$ which are slightly higher than my determination. However, Moffat and Vogt quote an error for their value of 0.05 mag, so the discrepancy is probably reasonable. For Ly 6 distance moduli in the literature range rather widely. Madore (1975) obtained 11.7 while Lyngå (1977) and van den Bergh and Harris (1976) both obtained about 10.8. Lyngå attributes the difference between his value and that of Madore to the handling of the problem of evolution. Additionally, van den Bergh and Harris attach a rather large uncertainty to their determination, $\pm 0.6$. In view of this, the present value is in very good agreement with the previous work. The color excesses derived in those three papers are in good agreement and correspond to $E(b-y) = 1.00$, which is slightly higher than the present determination.

From these comparisons of the present study with previous work, it appears that the agreement is generally quite good, although I am claiming higher precision than the previous studies were able to attain. This is largely due to the advantages of the intermediate-band system over the *UBV* system, which were discussed in the first paper of this series (Schmidt 1980).

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